

Final Report

Award **NAG5-9589**
Title **Reflectance & Thermal Infrared Spectroscopy of Mars:**
Relationship Between ISM & TES for Compositional Determinations
PI **John Mustard**
Awardee **Brown University**
COTR **Joseph Boyce**

Background, Motivation, and Objectives

Reflectance spectroscopy has demonstrated that high albedo surfaces on Mars contain heavily altered materials with some component of hematite, poorly crystalline ferric oxides, and an undefined silicate matrix. The spectral properties of many low albedo regions indicate crystalline basalts containing both low and high calcium pyroxene, a mineralogy consistent with the basaltic SNC meteorites. The Thermal Emission Spectrometer (TES) experiment on the Mars Geochemical Surveyor has acquired critical new data relevant to surface composition and mineralogy, but in a wavelength region that is complementary to reflectance spectroscopy. The essence of the completed research was to analyze TES data in the context of reflectance data obtained by the French ISM imaging spectrometer experiment in 1989. This approach increased our understanding of the complementary nature of these wavelength regions for mineralogic determinations using actual observations of the martian surface. The research effort focused on three regions of scientific importance: Syrtis Major-Isidis Basin, Oxia Palus-Arabia, and Valles Marineris. In each region distinct spatial variations related to reflectance, and in derived mineralogic information and interpreted compositional units were analyzed. In addition, specific science questions related to the composition of volcanics and crustal evolution, soil compositions and pedogenic processes, and the relationship between pristine lithologies and weathering provided an overall science-driven framework for the work. The detailed work plan involved co-location of TES and ISM data, extraction of reflectance and emissivity spectra from areas of known reflectance variability, and quantitative analysis using factor analysis and statistical techniques to determine the degree of correspondence between these different wavelength regions. Identified coherent variations in TES spectroscopy were assessed against known atmospheric effects to validate that the variations are due to surface properties. With this new understanding of reflectance and emission spectroscopy, mineralogic interpretations were derived and applied to the science objectives of the three regions.

Significance

Thermal emission spectroscopy will provide new global observations relevant to determining surface mineralogy of Mars over the course of the TES and THEMIS (2001) investigations. However, our experience in understanding emission spectroscopy of the martian surface is limited. In contrast, there are many decades of experience in the use of reflectance spectroscopy to study Mars. The results and lessons learned from reflectance spectroscopy provide an essential context for the exploration of Mars with TES. There are a number of well documented mineralogic investigations that have been made with ISM, as well as the identification of unanswered scientific questions. This provides the context to analyze TES emissivity. This investigation strengthened the Mars exploration goal of mineralogic mapping through a detailed analysis of the relationship between actual coregistered reflectance and emissivity measurements of Mars. There are three primary impacts of this research. The first is in providing a concrete spectroscopic and mineralogic guide based on reflectance to assist in the unraveling of mineralogic information from the TES measurements. The second is identifying which wavelength regions and to what extent reflectance and emission spectroscopy provide comparable mineralogic and/or surface property information, and where the information is complementary. The third impact is new insights into the mineralogy of the mafic to ultramafic volcanics, origin and evolution of pedogenic crusts, compositional diversity of mobile components on the surface, and the relationship between pristine and weathered products.

ISM Instrument, Data Reduction and Calibration

The ISM instrument is a scanning imaging spectrometer that covered the spectral range 0.76 to 3.16 μm (Bibring et al. 1989; Erard et al. 1991). This data set has been extensively analyzed over the last decade and there are over 40 engineering and science publications relate to the data or instrument (documented on the website ism.ias.fr). The technical issues related to the science analyses of these data (calibration, atmospheric compensation, aerosol effects) have been vigorously debated by the community as part of peer review during paper publication. As we have participated in many of these efforts, we are aware of the central issues, have dealt with the problems, and are entirely cognizant of the strengths and limitations of the ISM spectral data. Because these issues have been thoroughly addressed in the literature (see the ISM web site for a list) as well as previous proposals by the PI, in the interest of brevity they will not be restated here except where the issues have a direct bearing on the proposed research.

TES Instrument, Data Reduction and Calibration, and Merging with ISM

The TES instrument contains a Michelson interferometer that acquires measurements of thermal emission from 6-50 μm (1700-200 cm^{-1}) with either 5 or 10 cm^{-1} spectral resolution. It also contains two wide-band bolometer channels to measure

solar reflectance (0.3-2.7 μm) and thermal radiance (4-100 μm) at the same spatial resolution and coverage. The instruments are boresighted and all have an instantaneous field of view of 8.5 mrad. From the MGS mapping orbit, this corresponds to a spatial resolution of 3x6 km/pixel (the pixels are not square due to uncompensated spacecraft motion). The instrument is reported to have an absolute radiometric accuracy of better than $4 \times 10^{-8} \text{ W}/(\text{cm}^2 \cdot \text{sr} \cdot \text{cm}^{-1})$ and a signal to noise ratio better than 450 at 10 μm viewing a 270 K surface (Christensen et al., 1992; 2001a).

Approximately 8.5 million TES spectra were first selected from approximately 53 million for quality using factors including emission angle, temperature, spacecraft parameters, etc. The spectra were then deconvolved into atmospheric and surface components consisting of 2 dust and 2 cloud atmospheric endmembers, and hematite, Type I (Syrtis), and Type II (Acidalia) surface endmembers following previous works. These endmembers along with a blackbody successfully model the low albedo regions on Mars over the 73 bands (excluding the CO_2 absorption) from 233 to 1301 cm^{-1} (7.68 to 33 μm) (Bandfield et al., 2000). Subtraction of the atmospheric components from each of the original TES spectra yielded atmosphere-removed surface spectra. These spectra were then gridded into $0.5^\circ \times 0.5^\circ$ bins to create a global data set. To facilitate comparison of TES and ISM data, the TES spectra were first converted to reflectance using Kirchhof's Law. This allows the joined spectra to be displayed on a common axis.

The 64 band ISM spectra (0.77 to 3.14 μm) were matched to the TES half-degree grid via a nearest-neighbors approach. The resultant data cube contains both NIR and MIR spectra of the surface in 137 bands. Because the Phobos 2 mission ended prematurely, only a limited portion of the surface was covered. The 6 best data cubes of the 9 obtained with 22 km resolution were used here (locations are shown in Figure 3).

Analysis Results

The first step in the joint analysis of ISM and TES was to assess whether any significant changes in surface albedo had occurred between the two measurements, which would indicate regions where joint analysis would be invalid due to likely compositional changes on the surface. Comparison of TES vis-NIR bolometer measurements with the integrated average ISM reflectance for the gridded data set demonstrated that no significant changes in surface albedo occurred at the spatial scale of the merged data set, and thus joint analysis of the complete data set was warranted.

One of the most distinctive mineralogic signatures in the ISM data is the broad absorption centered near 2 μm related to Fe^{2+} crystal field absorptions. An equally distinct absorption related to pyroxene occurs near 1.0 μm , but this absorption may be modified by the presence of ferric oxides, olivine, and is most affected by slope effects

of aerosols. Mustard and Sunshine (1995) concluded that this feature was due to overlapping crystal field absorptions in both low and high calcium pyroxene, though others have argued that the absorption could be modeled by a singled pyroxene composition. Regardless, the strength of the 2 μm band is to first order related to the pyroxene concentration of the surface materials. TES spectra of dark regions dominated by Type I materials such as Syrtis Major exhibit a strong mineralogic feature near 22 μm related to pyroxene and mineralogic modeling indicates that high calcium pyroxene is likely responsible for this feature (e.g. Hamilton et al, 1997; 2001; Bandfield et al, 2000).

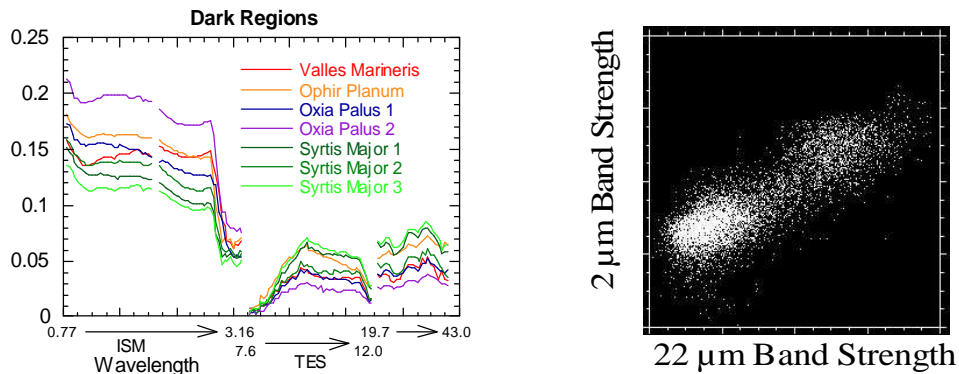


Figure 1. (left) Merged ISM (reflectance) and TES (1-emissivity) spectra for a range of regions that are interpreted to exhibit mineralogic diversity in ISM (Mustard et al., 1997). (right) Scatter plot of the strength of the 22 μm pyroxene feature (TES) vs. the 2 μm pyroxene feature (ISM).

The correlation between the 2 and 22 μm band strengths is shown in Figure 1 along with representative merged ISM-TES spectra. A consistent relationship between ISM and TES spectra is observed where surfaces that are bright in the NIR are dark at TES wavelengths and vice versa. The data in this scatter plot demonstrate a strong correlation between ISM and TES pyroxene band strengths. Cooper and Mustard (2002a) also showed that the 2 μm band strength is strongly correlated with the fractional abundance of Type I materials. In contrast with the band strength correlations, Mustard and Cooper (2002) showed that large variations in NIR spectral slope observed across Syrtis Major in ISM data have no apparent counterpart in TES spectra. This is interpreted to indicate that the electromagnetic interaction that leads to the observed NIR spectral slope occurs at a physical scale or is due to an absorption/scattering process to which TES is insensitive.

The joint analysis also reveals that regions characterized as dark red on the basis on their visible color and having distinct NIR spectral properties (e.g. Murchie et al., 1993; 2000) are correlated with TES spectral features indicative of cemented sulfate (Cooper and Mustard, 2002ac, Mustard and Cooper, 2002). Dark red regions have

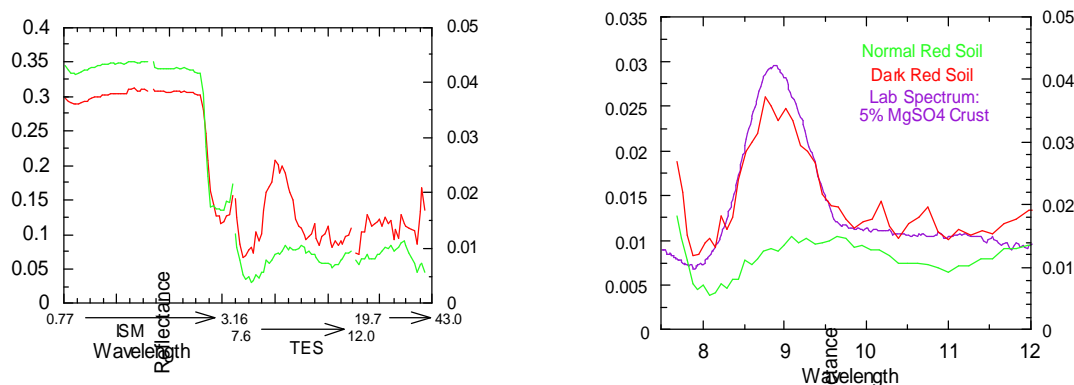


Figure 2. Pan spectra observations of normal bright red (green) and dark red (red) soils. Note the presence of a 8.9 μm emissivity band diagnostic of cemented sulfate. long been suspected of consisting of sulfate cemented soils (e.g. Arvidson 1989). The spectra shown in Figure 2 are for typical bright red soils and dark red soils as defined by Viking color and ISM properties. The TES spectra show subtle but consistent differences in spectral properties between these surfaces where the spectra of dark red soils exhibit a distinct absorption (reflectance peak) near 8.9 μm . This is well correlated with the shape and strength of a laboratory spectrum of a mixture of JSC-Mars 1 and MgSO_4 where the mixture was cemented by adding water and allowing the mixture to dry (Cooper and Mustard, 2002c). Thus we interpret the dark red surfaces with the TES spectral features to be sulfate cemented soils.

Peer Reviewed Articles:

- Head, J. W., J. F. Mustard, M. A. Kreslavsky, R. E. Milliken and D. R. Marchant, Recent Ice Ages on Mars 426, pp. 797-802, *Nature*, 2003.
- Milliken, R. E., J. F. Mustard, D. L. Goldsby, Viscous Flow Features on the Surface of Mars: Observations from High-Resolution Images, *J. Geophys. Res.* Vol. 108, No. E6, 5057 10.1029/2002JE002005, 2003.
- Cooper, C. D. and J. F. Mustard, New insights on Mars low albedo region composition from joint analysis of ISM and TES spectra, manuscript in preparation, 2004
- Cooper, C. D. and J. F. Mustard, Sulfates on Mars: Comparing TES and ISM results, manuscript in preparation, 2004

Abstracts

- Cooper, C. D. and J. F. Mustard, New insights on Mars low albedo region composition from joint analysis of ISM and TES spectra, *Lunar and Planetary Science XXXIII* #1873, 2002a
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